Bulk Density Characteristics of Grain Dust

C.S. Chang, C. R. Martin
MEMBER ASAE MEMBER ASAE

ABSTRACT

UTILIZING available information on pressure-density relationships of grain dust, models were developed to predict the density distribution and weight of grain dust in containers and in free standing piles. Similar approach can be applied to develop models for other compressible materials such as forage, hay, and cotton.

The weight of a self-packed dust column increased linearly as the depth increased. The dust holding capacity of a given container increased linearly as the mechanical pressure increased. At the same pile angle, the weight of a grain dust pile increased exponentially as the base diameter increased.

INTRODUCTION

Four hundred million tonnes of grain and oil seed were harvested in the U.S. in 1981 (Crop Reporting Board, USDA, 1982). Assuming that these grain and oil seed were handled twice and that 0.06 percent dust was collected by dust control systems during each handling, the total amount of collected grain dust would be almost half a million tonnes in that year.

Grain dust can be utilized as a feed ingredient in cattle and poultry rations (Behnke and Clark, 1979; Miller Publishing Co., 1979), burned under controlled conditions for heat (Chang et al., 1979), converted to combustible gas through gasification (Hoveland et al., 1982), or converted by composting into an organic soil conditioner for use in greenhouses and by gardeners (Chaing et al., 1981). The utilization of grain dust is increasing. Because of this trend it is expected that large quantities of dust will need to be handled, transported, and stored. Grain dust is quite compressible, and its consolidation results in a product of higher density which facilitates handling and storage. When a bulk of grain dust is loaded in a container or piled on the ground, material at any point in the bulk undergoes packing due to the weight of dust above it (self-packing) plus any mechanical pressure applied. Therefore, pressure and density vary within the dust. In order to design appropriate equipment for handling, transporting, and storing of dust, information on these packing characteristics of grain dust is required.

The objective of this study was to apply available information on pressure-density relationships of grain dust to develop models that predict density distribution and weight of grain dust in containers with and without applied mechanical pressures.

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The authors are: C. S. CHANG and C. R. MARTIN, Agricultural Engineers, U.S. Grain Marketing Research Laboratory, USDA-ARS, Manhattan, KS.

MATERIALS AND METHODS

A Dillon Testing Machine Model LWM was used previously to study the stress-strain behavior of grain dust under slow loading (Chang and Martin, 1983). The machine consisted of a sample container with smooth inner surface (5.7 cm high by 9.5 cm diameter), pressure and deformation monitoring systems, and a moving crossherad which moved at a constant speed of 3 mm/min during compression test. In that study, bulk densities of wheat dust, grain sorghum dust, and corn dust at moisture contents ranging from 9 to 15 percent and at pressures ranging from 0 to 120 kPa were determined, where an equation expressing bulk density of grain dust as a function of pressure was given as (Chang and Martin, 1983):

$$\rho = f_1(P) = A_1 - A_2 \, \mathrm{Exp}(-A_3 P) + A_4 P \quad \ldots\ldots\ldots \quad [1]$$

where

ρ = bulk density, kg/m^3
p = pressure, kPa
A_1, A_2, A_3, and A_4 are coefficients

Equation [1] was used in this study to obtain functional relationships between pressure and depth and between density and depth in a self-packed dust column (packing due to the weight of like material above it is referred to as self-packing). By utilizing these functional relationships, the density distribution and weight of a self-packed or press-packed dust column were then determined. The detailed procedures are discussed below:

Consider a small layer of material in a self-packed dust column, the dust weight in the layer can be expressed as:

$$dW = A \cdot dy \cdot \rho \quad \ldots\ldots\ldots \quad [2]$$

where

dW = dust weight in the layer, kg
A = cross section area of the dust column, m^2
dy = layer thickness, m
ρ = bulk density of dust, kg/m^3

From equation [2] one obtains:

$$dy = \frac{dW}{A \cdot \rho} = K_1 \frac{dP}{\rho}$$

or

$$y = \int_o^x K_1 \frac{dP}{\rho(P)} \quad \ldots\ldots\ldots \quad [3]$$

where

x = pressure, kPa
y = depth corresponding to x and measured from the top of the dust column, m
dP = pressure due to the weight dW, kPa
K_1 = constant, 102 kg/m^2 per kPa

Self-Packing

Substituting equation [1] into equation [3] and integrating the equation numerically, one can obtain the depth at any given pressure in a self-packed dust column. The corresponding density can be determined from equation [1]. By applying regression analysis using these data of depth vs pressure, an equation expressing pressure as a function of depth can be obtained as:

$$P = f_2(y) \quad \ldots\ldots\ldots\ldots \quad [4]$$

Furthermore, using the data of depth vs density, an equation expressing density in terms of depth can be obtained as:

$$\rho = f_3(y) \quad \ldots\ldots\ldots\ldots \quad [5]$$

The weight of a self-packed dust column can be determined by integrating equation [5] numerically:

$$W = A \int_0^{y'} \rho dy = A \int_0^{y'} f_3(y)dy \quad \ldots\ldots\ldots\ldots \quad [6]$$

or obtained from equation [4]:

$$W = K_1 AP = K_1 A f_2(y') \quad \ldots\ldots\ldots\ldots \quad [7]$$

where
y' = depth of the dust column, m
W = bulk weight of dust, kg

Press-Packing

For dust packed into a container by mechanical pressure, the density and pressure distributions in the container are equivalent to the density and pressure distributions in some section within a self-packed dust column (Fig. 1). The pressure at the top of this section generated by the weight of the dust above the section is equivalent to the pressure at the top of the container due to pressing. Therefore, the pressure and density at any depth within a container under pressing can be determined from the equivalent section within the self-packed dust column. The location of this section in the column can be determined from equation [3] for a given pressing pressure P_1 (Fig. 1):

$$y_1 = K_1 \int_0^{P_1} \frac{dP}{\rho(P)} \quad \ldots\ldots\ldots\ldots \quad [8]$$

and

$$y_2 = y_1 + h \quad \ldots\ldots\ldots\ldots \quad [9]$$

The weight of dust in the container under pressing can then be determined from the equivalent section using

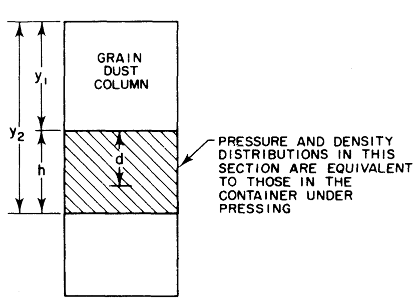

Fig. 1—Schematic diagram of a self-packed grain dust column.

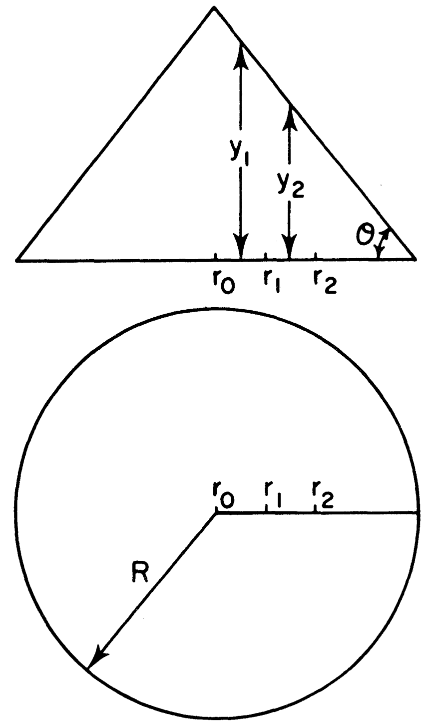

Fig. 2—Schematic diagram of grain dust pile.

equation [6]:

$$W = A \int_{y_1}^{y_2} f_3(y)dy \quad \ldots\ldots\ldots\ldots \quad [10]$$

or using equation [7]:

$$W = K_1 A \, [f_2(y_2) - f_2(y_1)] \quad \ldots\ldots\ldots\ldots \quad [11]$$

The distribution of density in the container can be obtained from equation [5]:

$$\rho = f_3(y_1 + d) \quad \ldots\ldots\ldots\ldots \quad [12]$$

where d is the distance measured from the top of the container.

Bulk Weight of Dust Pile

The weight of a conical shaped dust pile (Fig. 2) can be calculated by the summation of weights obtained from equation [7] for each concentric annular dust column in the pile represented by each annular thickness ($r_i - r_{i-1}$):

$$W = K_1 \sum_{i=1}^{n} A_i f_2(y_i) \quad \ldots\ldots\ldots\ldots \quad [13]$$

where
y_i = $[R - (r_i + r_{i-1})/2] \cdot \tan\theta$, depth of annular column i
A_i = $\pi(r_i^2 - r_{i-1}^2)$, cross-section area of annular column i
R = base radius of dust pile
r_i = radius of annular column i
θ = pile angle

RESULTS AND DISCUSSION

Moisture content, ash content, and the particle size distribution of the grain dust used previously in determining pressure-density relationships of grain dust

TABLE 1. MOISTURE AND ASH CONTENTS OF GRAIN DUST SAMPLES (CHANG AND MARTIN, 1983)

Kind of grain dust	Moisture content, % w.b.				Ash content, % d.b.
	Low	Intermediate	High	When collected	
Wheat 1	9.0	12.1	14.5	9.0	7.6
Wheat 2	9.5	12.6	15.3	9.7	13.9
Sorghum 1	9.3	12.3	15.2	9.6	8.5
Sorghum 2	8.9	11.9	14.0	9.3	8.6
Corn 1	9.8	12.1	14.7	10.4	1.0
Corn 2	8.7	12.3	15.0	9.6	4.7

TABLE 2. PARTICLE SIZE DISTRIBUTION OF GRAIN DUST SAMPLES (CHANG AND MARTIN, 1983)

Kind of grain dust	Particle size distribution, %				
	<125 μm	125-250 μm	250-500 μm	500-1000 μm	>1000 μm
Wheat 1	33.5	32.0	22.1	7.8	4.6
Wheat 2	33.9	17.5	17.9	16.3	14.4
Sorghum 1	67.6	13.2	9.0	5.8	4.4
Sorghum 2	77.8	6.8	3.8	4.4	7.2
Corn 1	87.7	6.4	3.2	1.9	0.8
Corn 2	80.9	4.8	3.3	4.9	6.1

Each value is the average of two samples.

are given in Tables 1 and 2 (Chang and Martin, 1983). Each kind of dust comprised two test lots collected from two different grain elevators. The coefficients in equation [1] for three kinds of grain dust at three levels of moisture content are given in Table 3 (Chang and Martin, 1983). Typical pressure-density curves from equation [1] for low moisture grain dust are shown in Fig. 3 (Chang and Martin, 1983).

Several forms of functional relationship were evaluated for equation [4] by non-linear regression analysis. The one which provided the best fit for pressure-depth data is:

$$P = f_2(y) = B_1 y + B_2 y^2 \quad [4]$$

Coefficients B_1 and B_2 for grain dust at three moisture levels are given in Table 4. The coefficients for the regression were significant at the 1 % level and the standard error of estimate ranged from 0.4 to 1.0 kPa. Plotted curves of pressure vs depth for low moisture dust are shown in Fig. 4. The pressure at any given point in a self-packed dust column increased almost linearly as the depth increased. The pressure at the bottom of a 10 m depth dust column ranged from 32 to 57 kPa depending on the kind of dust.

The form of functional relationship which provided the best fit for density-depth data for equation [5] is:

$$\rho = f_3(y) = C_1 - C_2 \mathrm{Exp}(-C_3 y) + C_4 y \quad [5]$$

Coefficients C_1, C_2, C_3, and C_4 for grain dust at three moisture levels are given in Table 5. The coefficients for the regression were significant at the 1 percent level and the standard error of estimate ranged from 0.6 to 3.3 kg/m^3. Plotted curves of density vs depth for low moisture dust are shown in Fig. 5. The shape of these curves was similar to that of density-pressure curves (Fig. 3) since the pressure-depth relationship was nearly linear. In general, the bulk density of dust increased rapidly in the first 4 m of depth. This increase in bulk density with depth declined gradually and reached a constant when the depth was increased from 4 to 6 m. For depth greater than 6 m, the bulk density increased slowly but linearly with increasing depth. It is to be noted that equations [4] and [5] are valid only within the pressure range (120 kPa) tested.

By using equations [4] and [7], weights of a self-packed dust column were obtained at various depths. For the same kind of dust, the difference between weight-depth curves at different levels of moisture was small. Plotted curves of weight vs depth for low moisture dust are given in Fig. 4. The weight of a self-packed dust column increased almost linearly as the depth increased. A 10 m height of dust column weighed 30 to 55 t per m^2 of base area, depending on the kind of dust. At the same depth, weight and pressure were lower for wheat dust than for corn dust and sorghum dust.

By using equations [8], [9], and [11], the weights of dust in containers under pressures up to 120 kPa can be determined. These results enable one to predict the dust holding capacity of a container at various pressures and to estimate the pressure requirement for a container to

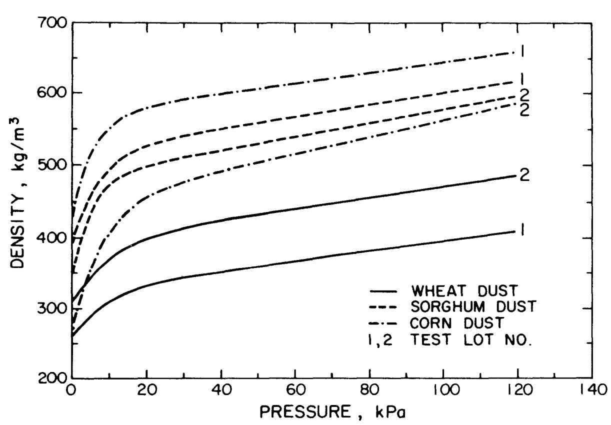

Fig. 3—Relationship between pressure and bulk density of grain dust (Chang and Martin, 1983).

TABLE 3. COEFFICIENTS FOR EQUATION EXPRESSING BULK DENSITY OF GRAIN DUST AS A FUNCTION OF PRESSURE (CHANG AND MARTIN, 1983)

Kind of dust	Level of moisture content*	Coefficients †			
		A_1	A_2	A_3	A_4
	Low	326	65	0.095	0.707
Wheat 1	Intermediate	330	76	0.093	0.933
	High	324	86	0.087	1.135
	Low	396	85	0.094	0.760
Wheat 2	Intermediate	396	92	0.099	0.898
	High	397	97	0.087	1.022
	Low	517	128	0.136	0.837
Sorghum 1	Intermediate	530	127	0.133	0.863
	High	525	138	0.127	0.980
	Low	483	140	0.188	0.939
Sorghum 2	Intermediate	491	148	0.170	0.964
	High	494	155	0.164	0.983
	Low	567	137	0.172	0.770
Corn 1	Intermediate	553	143	0.198	0.821
	High	550	147	0.196	0.901
	Low	447	181	0.123	1.154
Corn 2	Intermediate	436	180	0.118	1.071
	High	435	193	0.125	1.189

*See Table 1

† $\rho = A_1 - A_2 \mathrm{Exp}(-A_3 P) + A_4 P$

TABLE 4. COEFFICIENTS FOR EQUATION EXPRESSING PRESSURE AS A FUNCTION OF DEPTH OF A SELF-PACKED GRAIN DUST COLUMN.

Kind of dust	Level of moisture content*	Coefficient †	
		B_1	B_2
	Low	3.500	2.590×10^{-2}
Wheat 1	Intermediate	3.464	2.992×10^{-2}
	High	3.412	3.452×10^{-2}
	Low	2.900	1.859×10^{-2}
Wheat 2	Intermediate	2.856	2.502×10^{-2}
	High	2.719	3.031×10^{-2}
	Low	4.628	3.834×10^{-2}
Sorghum 1	Intermediate	4.750	3.998×10^{-2}
	High	4.637	4.552×10^{-2}
	Low	4.349	3.732×10^{-2}
Sorghum 2	Intermediate	4.370	4.041×10^{-2}
	High	4.357	4.257×10^{-2}
	Low	5.181	3.774×10^{-2}
Corn 1	Intermediate	5.055	3.773×10^{-2}
	High	5.014	4.065×10^{-2}
	Low	3.618	5.133×10^{-2}
Corn 2	Intermediate	3.483	4.886×10^{-2}
	High	3.424	5.302×10^{-2}

*See Table 1.
†$P = B_1 Y + B_2 Y^2$

hold a desired amount of dust. Fig. 6 shows the weight of dust in containers of 2 and 6 m in height for pressures ranging from 0 to 120 kPa. For a given height in a container, the dust holding capacity increased linearly as the pressure increased. At a given pressure, the holding capacity per unit height of container was slightly higher for a taller container than for a shorter one. Under a pressing pressure of 100 kPa, a 2 m height container held about 0.8 t of wheat dust, 1.2 t of sorghum dust and 1.3 t of corn dust per m^2 of container base.

By using equation [13], the weights of dust piles with various base diameters and pile angles were determined and are shown in Figs. 7 through 9. These curves enable one to estimate the quantity of dust in a dust pile if the base diameter and the pile angle, height or side of a dust pile are known. At the same pile angle, the weight of a dust pile increased exponentially as the base diameter increased. At a 40-deg pile angle, a dust pile with 16 m base diameter weighed about 135 t for wheat dust, 220 t for sorghum dust, and 245 t for corn dust.

TABLE 5. COEFFICIENTS FOR EQUATION EXPRESSING BULK DENSITY AS A FUNCTION OF DEPTH OF A SELF-PACKED GRAIN DUST COLUMN.

Kind of dust	Level of moisture content*	Coefficients †			
		C_1	C_2	C_3	C_4
	Low	321	61	0.283	2.60
Wheat 1	Intermediate	321	69	0.277	3.62
	High	312	75	0.257	4.52
	Low	392	82	0.327	3.31
Wheat 2	Intermediate	390	88	0.344	4.00
	High	389	90	0.304	4.68
	Low	515	128	0.594	4.60
Sorghum 1	Intermediate	527	126	0.600	4.88
	High	521	136	0.560	5.56
	Low	481	140	0.749	4.89
Sorghum 2	Intermediate	489	148	0.683	5.10
	High	491	155	0.654	5.23
	Low	566	138	0.827	4.55
Corn 1	Intermediate	551	144	0.914	4.76
	High	548	147	0.901	5.25
	Low	443	181	0.409	5.66
Corn 2	Intermediate	433	181	0.375	5.04
	High	430	194	0.386	5.65

*See Table 1.
† $\rho = C_1 - C_2 \operatorname{Exp}(-C_3 Y) + C_4 Y$

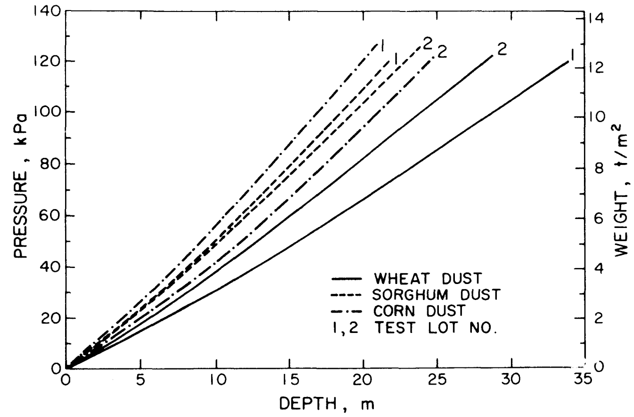

Fig. 4—Pressure at various depths in a self-packed grain dust column and bulk weight of dust in various depths of dust column.

Results obtained from this study were based on the pressure-density relationships of grain dust determined previously by using a Dillon Testing Machine (Chang and Martin, 1983). It should be noted that for a given pressure, bulk density of dust may vary with the speed of compression and the size of sample container. The effects of compression speed and container size on the pressure-density relationship of grain dust were not determined.

SUMMARY AND CONCLUSIONS

Functional relationships between pressure and density of wheat dust, sorghum dust, and corn dust at three levels of moisture content were used to obtain functional relationships between pressure and depth and between density and depth in a self-packed grain dust column. By utilizing these relationships, density distributions and bulk weights of grain dust in various sizes of containers under various pressures were determined. Results enable one to determine the dust holding capacity of a container under various pressures and to estimate the pressure required for a container to hold a desired amount of dust.

The weight of a self-packed dust column increased almost linearly as the depth increased. A 10 m height of

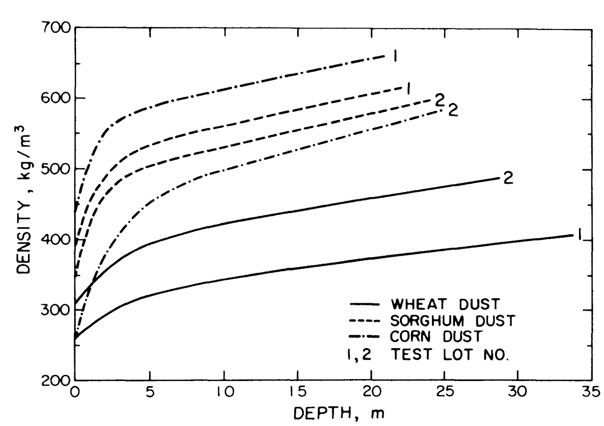

Fig. 5—Vertical density distribution of grain dust in a self-packed dust column.

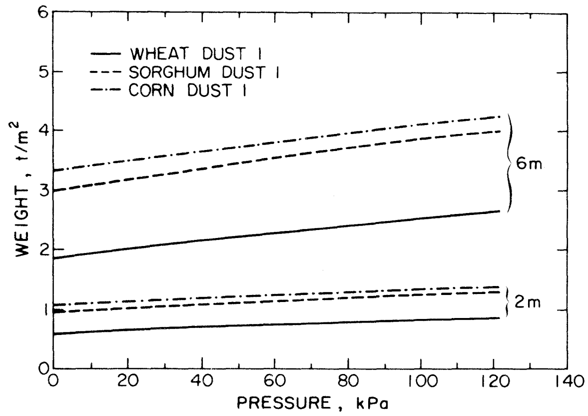

Fig. 6—Grain dust holding capacity of various sizes of container under various pressures.

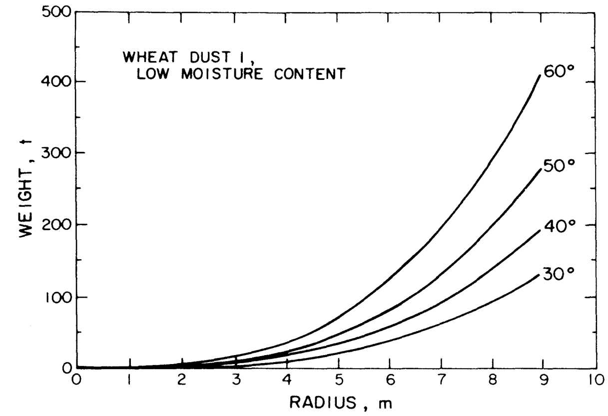

Fig. 7—Bulk weight of wheat dust pile with various pile angles and base radius.

dust column weighed 30 to 55 t per m² of base area depending on the kind of dust. The effect of moisture content on bulk weight of grain dust was small.

The shape of the density-depth curve for grain dust was similar to that of density-pressure curve. The pressure-depth relationship of grain dust was nearly linear.

The grain dust holding capacity of a given size of container increased almost linearly as the applied pressure increased. At a given applied pressure, the holding capacity per unit height of container was slightly higher for a taller container than for a shorter one.

At the same pile angle, the bulk weight of a grain dust pile increased exponentially as the base diameter increased.

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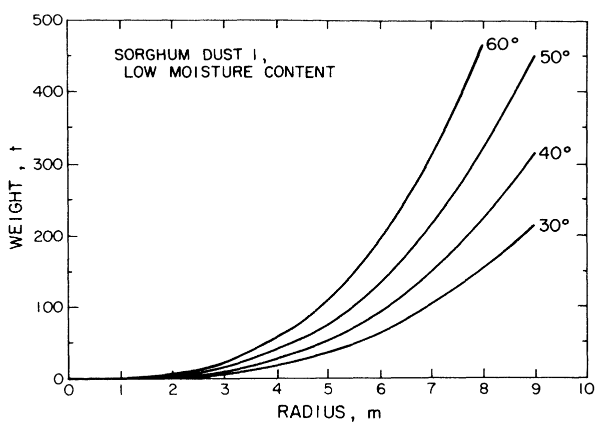

Fig. 8—Bulk weight of sorghum dust pile with various pile angles and base radius.

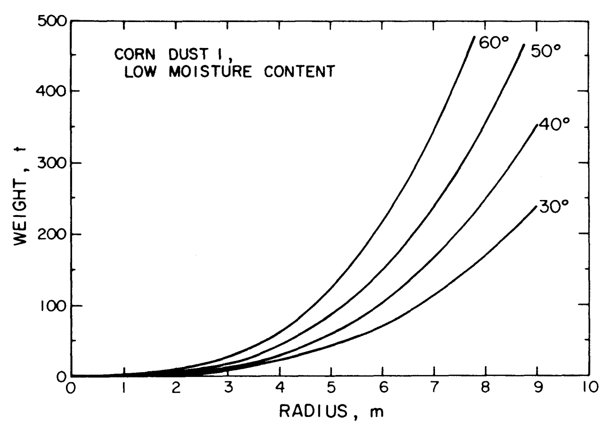

Fig. 9—Bulk weight of corn dust pile with various pile angles and base radius.